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BLM Gas Variability Study Final Report (Public)

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May 21, 2010

Purpose and Conclusions

The purpose of this report is to: 1) determine heating value variability on a formation-by-formation basis; 2) determine the measurement uncertainty due to gas variability; 3) identify the critical factors that cause increased variability; 4) establish gas sampling frequency requirements that will minimize the risk of mis-measurement and mis-reporting; and, 5) quantify the potential fiscal impacts of gas variability. This report is not intended to quantify the uncertainty due to sampling and analysis methodology.

The conclusions are as follows:

- Computer simulation and the data collected show that heating value variability is random rather than cyclic and shows no dependence on any variable analyzed (age, type, formation, pressure , temperature, etc.);
- The uncertainty in heating value and relative density for any given gas sample taken does not depend on the frequency of sampling; it only depends on the historical variability of the heating value and relative density;
- The uncertainty in heating value and relative density *averaged* over a period of time is dependent on sampling frequency and an equation was developed relating average heating value and relative density uncertainty to sampling frequency;
- Based on current requirements (i.e. annual sampling), the uncertainty in royalty due to volume measurement and sampling is ±5.09%, or ±$127 million, based on 2008 revenues;
- There are numerous options on how to address sampling frequency to minimize the resulting uncertainty in heating value.

Background

On December 17, 2007, the U.S. Department of Interior, Royalty Policy Committee, Subcommittee on Royalty Management, published a report entitled "Mineral Revenue Collection from Federal and Indian Lands and the Outer Continental Shelf" [RPC report]. This report included over 100 recommendations to improve the way Federal and Indian mineral revenues are collected and verified. Many of these recommendations relate to the determination and reporting of gas heating value. Recommendation 3-1 states:

> *"MMS and BLM should develop a procedure to determine the potential BTU variability of produced natural gas on a by-reservoir or by-lease basis, and estimate the implications for royalty payments."*

In addition, one of the milestones for the completion of Recommendation 3-1 is:

> *"Fluids Team to use the [variability] report to develop gas sampling frequency requirements and to analyze the effect of BTU and gravity variation on overall measurement uncertainty."*

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Recommendation 3-2 goes on to state:

> *"...MMS and BLM should determine what the proper BTU sampling and analysis frequency should be and develop language for the revision of Onshore Order 5 and MMS Regs. 250.1203..."*

This report is an attempt to address these recommendations.

Before discussing heating value variability in any detail, it is important to emphasize the significance of heating value on royalties. For virtually all Indian and Federal gas produced, royalty due on production is determined with the following equation:

$$\$R = RR \times V \times HV \times P \qquad \text{(Eq. 1)}$$

Where:

$\$R$ is the royalty due on gas produced from a given case for a given month
RR is the lease royalty rate (usually 12.5%)
V is the volume of gas produced (Mcf)
HV is the heating value of the gas that is produced (Btu/scf)
P is the price, or monetary value of the gas determined by MMS ($/MMBtu)

While the volume (V) produced from a lease or case is determined by a permanently installed meter that must meet a variety of standards, the heating value (HV) is typically (on-shore) determined by taking a spot sample of the gas and having it analyzed. The analysis determines the composition of the gas and then uses a standard equation[1] to calculate the heating value. In addition to heating value, the gas analysis is also used to calculate the relative density and supercompressibility of the gas; both of which are used by flow meters in the determination of volume.

While BLM has standards in place for the volume measuring equipment, BLM's only requirement for gas sampling is that it be done once per year[2]. BLM has no requirements for sampling methods, sampling locations, analysis methods, or reporting basis. Referring again to Equation 1, it can be seen that uncertainty in the heating value will have the same affect on royalty as uncertainty in volume.

Uncertainty in heating value comes from two sources: 1) the equipment and methodology used to obtain, analyze, and report heating value, and 2) statistical influences when taking spot samples. This report focuses on the statistical influences of spot sampling. Inclusion of sampling and analysis standards in the rewrite of Onshore Order 5 will address the equipment and methodology aspects.

Data Collection

In order to determine heating value variability, it was first necessary to obtain a number of gas analyses that would provide the statistical basis for the study. Federal Points of Measurement (POM) were chosen that provided a reasonable range of reservoir types, flowing conditions, surface and downhole plumbing configurations, and age. In May, 2009, Written Orders to the operators of the selected POMs were sent out asking for the gas analyses for the past 6 years or the life of the meter, whichever was longest. Table 1 summarizes the records requested and the records received.

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[1] API Chapter 14.5, *"Calculation of Gross Heating Value, Relative Density, Compressibility and Theoretical Hydrocarbon Liquid Content for Natural Gas Mixtures for Custody Transfer"*, API, Third Edition, January, 2009
[2] Onshore Oil and Gas Order Number 5, 1989, III.C.23

Field Office	# of POM requested	# of POM received	# of POM used	# of samples
Buffalo, WY	62	42	42	221
Farmington, NM	65	64	59	549
Glenwood Springs, CO	24	9	9	24
Pinedale, WY	81	52	46	513
Rawlins, WY	46	38	37	292
Vernal, UT	44	32	24	296
TOTAL	322	237	217	1895

Table 1 – Data summary

As shown in Table 1, certain records were received that could not be tied to a known lease or case number, or were not included in the original request. Because the conditions of these meters were not known, these records could not be used for most of the analysis.

Once the data were received, they were key entered into an Excel spreadsheet and then imported into an Access database for manipulation and analysis. Some data filtering and editing was also performed.

Heating Value Variability By Formation

This analysis is intended to address part of Recommendation 3-1 in the RPC report, which asks BLM to develop a procedure to determine BTU variability of produced natural gas on a by-reservoir or by-lease basis. It was determined that there was insufficient data to perform an analysis on a lease-by-lease basis. BLM currently manages about 23,000 producible oil and gas leases. The data for 237 POMs received (see Table 1) covers 193 different leases. Therefore, the data for this analysis represents less than 1% of the total number of leases that BLM manages, making it virtually impossible to perform an analysis on a lease-by-lease basis.

It was also not possible to perform the analysis on a reservoir-by-reservoir basis because of the difficulty in defining a "reservoir" and in obtaining data by reservoir. Instead, it was decided to perform the analysis on a formation-by-formation basis as this is a better defined parameter and the producing formation data are readily available to BLM.

The gas analysis data base was first sorted on formation, meter name, and sample date. For each formation, the average heating value of all the samples taken from that formation was calculated along with the standard deviation. The scatter in the heating values was determined at the 95% confidence level using a *student t* -distribution. For example, the Almond formation has an average heating value of 1109.5 Btu/scf with a 95% confidence variation of ±4.91%. This indicates that 95% of the heating values obtained were between 1055.1 Btu/scf and 1164.0 Btu/scf. Use of the student t-distribution allows for meaningful analysis of small data sets. Table 2 summarizes the this analysis (note that variation is not calculated when there are less than 5 samples).

Formation	#meters	#samples	Average Heating Value (Btu/scf)	Variation 95% (±%)
ALMOND	6	31	1109.55	4.91
ALMY	4	29	1186.04	11.03
ANDERSON COAL	5	28	902.65	19.12
BAXTER	3	15	1115.99	9.40
BEAR RIVER	4	4	1113.62	
BEAR RIVER/FRONTIER 2	1	52	1126.95	2.64
BIG GEORGE COAL	5	21	945.39	1.99
CANYON COAL	3	18	942.64	15.48
CANYON COAL (LOWER)	1	1	981.60	
CARMEL	1	11	1037.74	1.13
CASTLEGATE	2	24	1141.63	9.07
CEDAR MOUNTAIN	1	3	1029.75	
CHACRA	5	31	1208.99	11.86
COOK COAL	2	6	908.95	48.30
COW CREEK	1	5	1118.44	5.57
DAKOTA	9	47	1240.95	17.48
DAKOTA / MORRISON	1	7	1039.01	0.94
DEEP CREEK	1	1	988.49	
DIETZ 3 COAL	1	4	957.71	
ERICSON	1	4	1115.10	
FARMINGTON	2	10	1056.70	8.67
FELIX COAL	1	4	920.44	
FORT UNION	3	22	923.30	5.32
FORT UNION COAL	2	25	958.77	3.96
FRONTIER	11	78	1093.39	7.53
FRONTIER 2	2	9	1123.27	4.72
FRUITLAND	9	104	1044.44	15.08
FRUITLAND COAL	1	22	956.29	1.14
GALLUP	4	27	1080.17	17.75
GREEN RIVER	2	11	1041.22	8.93
HILLIARD/BAXTER	1	47	1160.95	3.65
KIRTLAND	1	2	967.20	
KNOBLOCH COAL	1	18	938.69	0.94
LANCE	2	8	1190.49	3.23
LANCE POOL	5	29	1083.96	1.73
LANCE POOLTRANSI LANCE POOL	1	13	1089.82	0.43
LANCE/WARDELL	1	11	1145.56	0.77
LEWIS	11	87	1143.54	9.33
LOWER CANYON COAL	1	10	944.11	2.14
LOWER COOK COAL	1	4	971.58	
MANCOS B	1	4	1314.96	
MESAVERDE	26	213	1146.28	9.06
MESAVERDE 1	5	44	1184.63	19.28

Formation	#meters	#samples	Average Heating Value (Btu/scf)	Variation 95% (±%)
MESAVERDE 1/LANCE	1	6	1085.00	0.57
MIDWEST COAL	2	2	893.77	
MONARCH COAL	1	3	979.67	
MORGAN	1	4	993.49	
MORRISON	1	12	1110.63	0.73
MUDDY	3	18	1155.64	24.60
NACIMIENTO	1	38	862.14	5.53
NIOBRARA	1	2	1420.13	
OJO ALAMO	3	33	1041.75	2.06
PARKMAN	1	3	1593.47	
PICTURED CLIFFS	7	71	1154.36	15.47
PINON FRUITLAND SAND	1	5	1171.40	1.35
POINT LOOKOUT	5	37	1047.90	16.05
ROBERTSON COAL	1	27	1050.24	13.83
S1-FRONTIER 1/S2-BEAR RIVER	1	7	1150.09	1.71
S1-FRONTIER 1/S2-FRONTIER 2	2	13	1105.29	1.57
S1-FRONTIER-MUDDY/S3-BAXTER	1	5	1140.63	2.01
SAN JOSE	3	26	1108.75	12.85
SHANNON	2	8	1163.82	13.70
SKULL CREEK	1	3	1300.97	
SMITH COAL	1	2	987.00	
TANSILL	1	5	1179.81	1.35
TOCITO	1	19	1347.50	18.73
TRANSITION	2	26	1242.82	4.69
TRANSITION/MESAVERDE 1	1	5	1198.03	9.68
TURNER	3	15	1387.71	8.69
UINTA	1	11	1015.09	0.12
UPPER COOK COAL	1	6	953.22	9.72
WALL COAL	1	2	935.59	
WASATCH	9	75	1142.01	17.76
WASATCH G SAND	1	2	1069.87	
WILLIAMS FORK	2	11	1118.92	6.36
WOLF CAMP	1	4	1113.58	
WYODAK COAL	1	12	901.45	6.34

Table 2 – Heating Value Variation by Formation

Sampling Methods

Referring to Equation 1, royalty payments are directly affected by the measured heating value of a gas. A 10% error in the measured heating value will result in a 10% error in royalty payment as long as the errant gas analysis report is in effect.

It is not unreasonable to expect that heating value will vary over time depending on geographic location within a formation, changing reservoir conditions, changing ambient conditions, changing flowing conditions, or changing gas streams for meters that measure more than one well. Stratification or segregation of heavier and lighter gas can occur in a single formation causing variation in the gas stream over time or as a function of producing depth or location of the well within the formation.

To account for changes in heating value over time, only three different measurement methodologies have been adopted by industry: on-line gas chromatographs, composite sampling, and spot sampling (cylinder and portable gas chromatograph).

One method of determining heating value is through continuous measurement, which can be approximated with an on-line gas chromatograph. This device automatically samples and analyzes the gas stream every few minutes and then transmits the calculated heating value, relative density, and composition to the flow computer. The flow computer multiplies each measured heating value by the volume of gas measured to integrate the energy content of the gas over a reporting period. On line gas chromatographs are, however, expensive and are typically only found on high-volume sales meters.

A second method of determining heating value is with a flow-proportional composite sample. This is a device that allows a small sample of gas to be added to a sample cylinder at even increments of volume measured by the flow meter. Once the sample cylinder is filled, it is taken to a lab where the gas is put through a gas chromatograph to determine the composition. Over a period of time, the sample cylinder will contain a true volume-weighted average composition from which heating value and relative density are calculated. As with on-line gas chromatographs, these devices also tend to be found only on higher volume sales meters.

The third form of sampling is with a spot sample taken at some interval of time (minimum of once per year for BLM). A spot sample is taken by either filling a sample cylinder and taking it to a lab for analysis or bringing a portable gas chromatograph to the field and temporarily connecting it directly to the sample port. Through inquiries with BLM Field Offices, it is estimated that at least 95% of heating values for onshore Federal and Indian gas are determined through spot sampling.

Uncertainty and Bias Due to Spot Sampling

The uncertainty of heating value and relative density is dependent on the sample and analysis equipment and methodology for all sampling methods described above. Sample bias is minimized by following published industry standards that are based on research and field experience[3]. However, because spot sampling is essentially a random snapshot in time, it also includes a statistical component of uncertainty. This "statistical" source of uncertainty is the focus of this study. Total uncertainty in heating value (U_{HV}) taken by spot sampling is the combination of the uncertainty due to the equipment and procedures used (U_{ep}) and the statistical uncertainty (U_s). In equation form, total uncertainty is determined as follows:

(Eq. 2)

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[3] Although BLM does not currently incorporate or enforce these standards, this is beyond the scope of this report and is being addressed in other RPC recommendations.

Online gas chromatographs and composite samplers effectively integrate the composition over time and do not include the statistical component.

To demonstrate the uncertainty caused by spot sampling, assume that the true heating value at a particular meter varies with time as shown in Figure 1. Also assume that a single spot sample is taken at some point during the year shown and the heating value derived from the spot sample is used for royalty determination for the entire year. From Figure 1, the heating value used for royalty determination could be anywhere between 950 Btu/scf and 1050 Btu/scf, depending on the time and date the sample was taken. This gives an uncertainty of ±50 Btu/scf, or ±5%. This statistical uncertainty would be in addition to the uncertainty due to the sampling equipment and procedures used to obtain the sample and analysis.

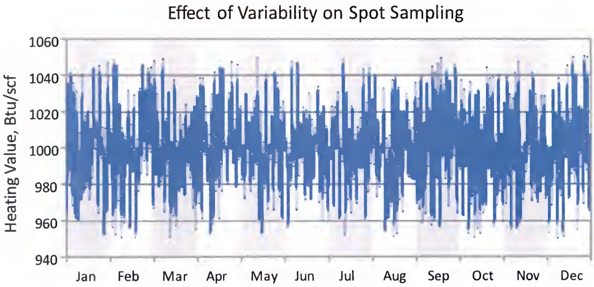

Figure 1

Variability patterns

One of the first hurdles in this analysis is determining the type of variation that is present. Is the variation highly random and variable such as that shown in Figure 1, or is it more cyclic as shown in Figure 2 (reflecting a possible seasonal fluctuation, for example). From Figure 2, it can be seen that if samples were taken frequently – once a week for example - the change in heating value between samples would be minimal. If, on the other hand, samples were only taken once or twice per year, the odds of a much larger fluctuation between heating values would be greater. To demonstrate this effect, a computer simulation was developed that generated random cyclic patterns similar to that shown in Figure 2. Then, virtual samples were taken at different frequencies and the average difference in heating values from sample to sample were plotted for each frequency. The results of this simulation are shown in Figure 3, where each dot represents the difference in heating value between the sample taken and the previous sample taken. There is a distinct relationship between sample frequency and maximum change in heating value between samples (shown by the red line). However, once the time between samples exceeds 60 days, or about a 2/3 of the cycle frequency (from Figure 2), the relationship no longer applies and becomes random.

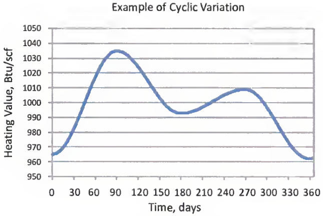

Figure 2

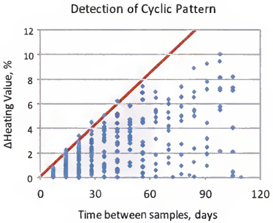

Figure 3

The same type of analysis was done on the data collected in an attempt to indentify some type of relationship between sample frequency and change in heating value between samples. If a relationship similar to that shown in Figure 3 is apparent, it could indicate that heating value variation is cyclic in nature. This analysis was done on a formation-by-formation basis. Graphs of the four formations with the greatest amount of data are shown in Figures 4a through 4d. None of these figures demonstrate any relationship between sampling frequency and change in heating value, nor did any of the other formations analyzed. This leads to the conclusion that there is no evidence indicating that heating value variation as a function of time is cyclic in nature.

It is possible that the uncertainty in the sampling and analysis methods mask any actual variation in heating value or it is possible that the cyclic pattern, if it exists, is shorter than the sampling frequencies analyzed. Regardless of the cause, however, it is assumed for the remainder of the study that heating value variation is completely random, as shown in Figure 1.

Uncertainty of single heating values

Going back to the pattern in Figure 1, now assume that instead of a single annual sample, a monthly sample is taken sometime within each month and used to report the heating value on OGOR B[4] for that month. The range of values that could be obtained for each sample is shown by Table 3. From Table 3, it can be seen that increasing sample frequency from once per year to once per month has very little effect on the uncertainty of a sample.

To test this hypothesis – that sample frequency has little impact on individual values of heating value uncertainty – the data collected were again analyzed. First, the data were sorted to exclude meters where there were less than 5 samples. Then, the variability of the heating values for each meter was calculated using a student t-distribution as shown by Equation 3 (See Appendix 1 for an example of this method).

(Eq. 3)

where:

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[4] "OGOR B", is the Oil and gas Operator Report, Part B, which is an MMS form used to collect volume and heating value on which royalty is calculated for a lease, participating area, or communitization area.

U_{HV} is the uncertainty (95% confidence level) of the heating value, ±%
σ is the standard deviation of the previous samples, ±%
t_{dist} is the "student t-distribution" function shown in Appendix 2

Month	Heating Value Range (Btu/scf)		Uncertainty
	High	Low	(±%)
January	1047	953	4.70
February	1048	953	4.75
March	1050	951	4.95
April	1049	952	4.85
May	1050	952	4.90
June	1046	958	4.40
July	1049	951	4.90
August	1040	952	4.40
September	1049	958	4.55
October	1045	957	4.40
November	1047	956	4.55
December	1050	951	4.95

Table 3

Note that Equation 3 is used to determine the *total* uncertainty in heating value (U_{HV}) because the variability in the historical data include the effects of both statistical uncertainty (U_s) and uncertainty due to the equipment and procedures used (U_{ep}). Finally, the calculated variability of the heating value for each meter, using Equation 3, was plotted against the average time between samples for that meter as shown in Figure 5. Again, there is no apparent dependence of variability on sampling frequency, which not only supports the hypothesis described above, but also reaffirms the apparent random nature of heating value variations.

Uncertainty of average heating value

Another way to look at statistical uncertainty due to spot sampling is the uncertainty in *average* heating value taken over some period of time, rather than the uncertainty of any given sample. For the pattern shown in Figure 1, a time was randomly picked within each month when a virtual sample was taken. This is shown by the yellow dots in Figure 6. Table 4 lists the heating values obtained from the 12 random monthly samples. From Table 4, the *average* heating value for the year is 995.8 Btu/scf, whereas the true average of the data set is 999.9, for an error of only 0.41%. By taking 12 monthly samples, the uncertainty in heating value due to spot sampling over a year's time has been reduced from ±5% to only ±0.41%.

Of course, had another pattern been used in Figures 1 and 6, or other sampling points selected, this averaging error could have been lower than the true average, higher than the true average, or even the

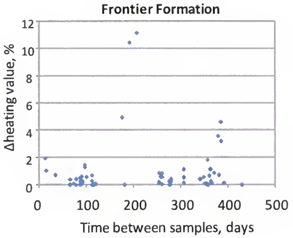

Figure 4a

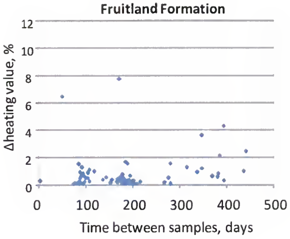

Figure 4b

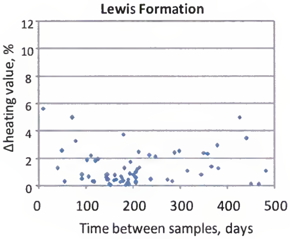

Figure 4c

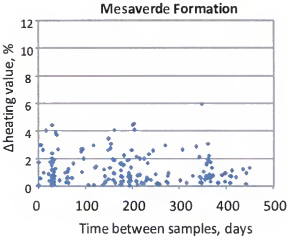

Figure 4d

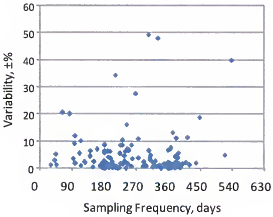

Figure 5

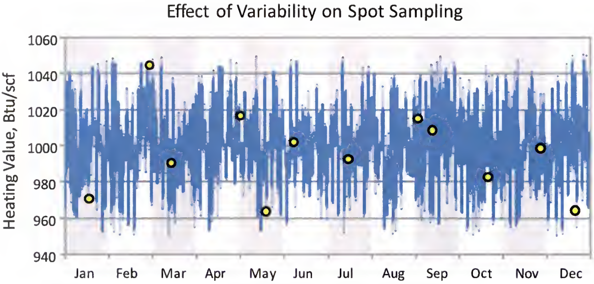

Figure 6

Sample Date	Heating Value (Btu/scf)
January 16	971.6
February 27	1042.3
March 12	990.5
April 29	1016.0
May 16	965.0
June 5	1001.5
July 12	993.0
August 29	1014.0
September 9	1007.7
October 16	983.5
November 22	998.6
December 16	965.6
Average	**995.8**

Table 4

same as the true average. Therefore, this averaging error actually becomes a *range* of potential error based on the specific case. A "*range of potential error*" is the definition of uncertainty; therefore, there is uncertainty associated with the statistical probability of spot sampling.

A general conclusion can be drawn that the more samples that are taken over a period of time, the closer the average of the samples will be to the true average. The longer the time between samples, the fewer samples are collected. While the monthly sampling results in 12 data points for the year, there would only be 1 data point if an annual sample was taken. The fewer data points there are in an average, the higher the probability that the average will not accurately represent the data set. This is the basis of the remainder of this study – establishing a relationship between sample frequency and the average heating value uncertainty over a period of time.

The selection of a time frame for which an average is calculated is somewhat arbitrary. A period of 1 year was used in this study. The selection of a shorter averaging time will result in a higher uncertainty for a given sampling frequency and a longer averaging time will result in lower uncertainty than those given.

Computer Modeling

To quantify the uncertainty of average heating value due to variability, a computer "Monte Carlo" model was developed. The model first creates a random pattern of heating values over a 1-year span of time in one-hour increments, similar to Figure 1. Then, virtual samples of heating value are taken from the pattern at sampling intervals ranging from once per day to once every 360 days, in one day steps. An average heating value for the pattern is determined and recorded for each sampling frequency. Once that is complete, a new pattern is generated and samples are once again taken. This process is repeated 100 times to determine the relationship between sampling frequency and uncertainty.

For each run of the model, the maximum amount of variation along with the central value can be assigned. A central value of 1000 Btu/scf was used for all runs, and four levels of maximum variation were used in the analysis: ±500 Btu/scf, ±100 Btu/scf, ±50 Btu/scf, and ±10 Btu/scf. A variation of ±0 Btu/scf was also run to ensure the average and standard deviation calculations were performed correctly.

Model results include the average heating value for each sampling frequency for each run of the model. Figure 7 shows the results from 10 runs (100 runs was too cumbersome to plot) for a maximum assigned pattern variation of ±50 Btu/scf. From Figure 7, it can be seen that for very short sampling frequencies, the average heating value taken over a year has much less scatter than for samples of the same data taken less frequently. For example, the range of possible average heating values for a 30-day sampling frequency is about ±8 Btu/scf, whereas the range is about ±30 Btu/scf when samples are taken annually. Clearly, there is a relationship between sample frequency and range of error, or uncertainty, of average heating value taken over a span of time. This is a statistical uncertainty that is unique to spot sampling as it has nothing to do with the methods or equipment used to obtain heating values in the field.

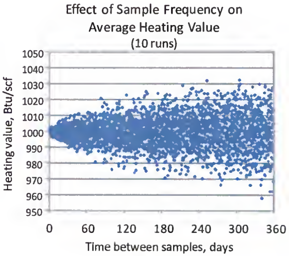

Figure 7

To quantify this relationship, the results of the model were sorted by sampling frequency and by run as shown in Table 5. For each row of data, the amount of scatter for that sampling frequency was calculated as two times the standard deviation of the values (2σ). For a large data set, a 2σ value

Sample Frequency (days)	Average Heating Value (Btu/scf) for Model Run #...								2σ Variation (±%)
	1	***2***	***3***	***4***	***5***	***6***	***7...***	***100***	
1	1000.1	1000.3	1000.0	999.7	1000.2	999.9	999.6	1000.1	0.1615
2	999.5	999.7	1000.2	100.0	999.8	1000.0	999.4	999.9	0.2284
3...	999.9	1000.0	999.7	1000.9	1000.2	999.4	999.4	1000.1	0.2797
360	973.5	984.0	1010.8	1001.5	1024.9	998.7	1003.3	989.0	3.0642

Table 5– Sample Model Results for a Random Variation of ±50 Btu/scf

yields a 95% confidence level; in other words, 95% of the data is between the (+) and (-) value given. Similar calculations were done with the random pattern variation set at ±100 Btu/scf and ±10 Btu/scf. Predictably, the higher the variation set in the model, the greater the 2σ variation for a given sample frequency and visa versa. Figure 8 shows a graph of 2σ variation (uncertainty) as a function of sample frequency and degree of random pattern variation. The blue dots represent the 2σ variation in the model output as shown in Table 5 and the red lines are curve fits of each set of data. The 2σ variation of the actual random heating value patterns was also calculated ($V_{95\%}$).

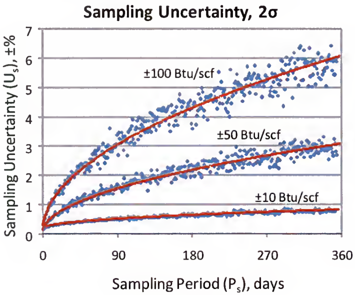

Figure 8

A general equation (shown by the red lines in Figure 8) for each data set was determined as follows:

(Eq. 4)

Where:

U_s is the statistical spot sampling uncertainty
C is a constant that is a function of the data variability, $V_{95\%}$ (see Table 6)
P_s is the time between samples, days
P_a is the averaging period, days

Variation in Random Pattern (±Btu/scf)	2σ Variation in Random Pattern (±%)	"C" for Equation 2
100	11.54	1.097
50	5.772	5.489
10	1.154	10.975

Table 6

It was then determined that the constants, "C", from Table 6 had a linear relationship with the 2σ variation in the random patterns generated by the model. Therefore, a single equation relating statistical sampling uncertainty (U_s) to sampling period (P_s), averaging period (P_a), and 2σ variation in the sampling data ($V_{95\%}$) was derived as shown by Equation 5:

(Eq. 5)

Application of the Computer Model

Use of the computer model demonstrates that uncertainty in average heating value due to sampling frequency is predictable and quantifiable. To apply the uncertainty equation (Eq. 5), the primary unknown is the variability of the heating value data ($V_{95\%}$), which can be determined using historical heating values and standard statistical methods described by Equation 3 and as shown in Appendix 1. Once this has been determined, Equation 5 can be used to determine the uncertainty in average heating value at various sampling frequencies. For a variation ($V_{95\%}$) of ±2.47% from the example in Appendix 1, the sampling uncertainty at various sampling frequencies can then be calculated as shown in Table 7 (assume a 1-year averaging period).

Because historical data is used to determine the variability, and the historical data includes the uncertainty effects of both statistical variability (U_s) and the equipment and procedures used (U_{ep}), the sampling uncertainty obtained using Equation 5 is the total uncertainty in heating value (U_{HV}).

Sample Frequency (days)		$V_{95\%}$	1-year average Heating Value Uncertainty (±%)
30	0.2867	2.47	0.668
60	0.4054	2.47	0.945
90	0.4966	2.47	1.157
180	0.7022	2.47	1.636
365	1.0000	2.47	2.330

Table 7

This methodology was applied for each meter measuring gas from the formations presented in Table 1. Appendix 3 shows the heating value uncertainties of each meter as a function of sampling frequency.

The exact same methodology can be used to determine the uncertainty in relative density as follows:

(Eq. 6)

where U_{Gr} is the uncertainty in relative density. Appendix 4 shows the relative density uncertainties. Meters where there are less than five samples were excluded from the analyses.

Royalty Implications

Referring to Equation 1, royalty is based on both volume and heating value. Errors in either value will result in proportional errors in royalty. Likewise, uncertainty in volume and heating value will result in uncertainty in royalty. For the purpose of this study, it will be assumed that biases in both volume and heating value have been minimized by following industry standards. This assumption, however, is not currently applicable because BLM does not have any standards for sampling and analysis.

While the focus of this study has been on heating value uncertainty, this analysis and uncertainty determination method applies equally to relative density determination, as shown in Appendix 4. Relative density is important because it is used in the determination of volume. Therefore, uncertainty in sampling results in uncertainty to both volume and heating value.

In addition to relative density, sampling uncertainty also affects the calculation of supercompressibility, which also affects volume calculation. However, because the uncertainty effects on supercompressibility are minor compared with relative density, this effect is not included in this study.

Based on the data and results in Appendices 3 and 4, an average uncertainty in both heating value and relative density, based on the current requirement for annual sampling, was determined as follows:

Uncertainty in heating value (U_{HV}): ±3.58%
Uncertainty in relative density (U_{Gr}): ±4.03%

In addition, the uncertainty in volume, excluding the effects of relative density, is currently limited to ±3% for meters measuring more than 100 Mcf/day, through the various statewide Notices to Lessees (NTLs). Overall uncertainty of both volume and heating value, which would also reflect the uncertainty in royalty is the root-sum-square of these three sources of uncertainty and is determined as follows:

Where:

U_r is the uncertainty in royalty, ±%
X_v is the sensitivity coefficient for volume uncertainty (1.0)
U_v is the uncertainty in volume, ±%
X_d is the sensitivity coefficient for relative density (0.5)[5]
U_d is the uncertainty in relative density, ±%
X_{HV} is the sensitivity coefficient for heating value (1.0)
U_{HV} is the uncertainty in heating value, ±%

= ±5.09%

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[5] In the flow equation, the relative density is taken to the 0.5 power; sensitivity coefficient is generally taken as the exponent of the variable.

Given the 2008 total onshore Federal and Indian royalty income of about $2.5 billion, the total uncertainty due to volume and heating value is ±$127 million, based on a 1-year average.

If, for example, the sampling frequency was increased to monthly for all meters used in this study, the uncertainty in royalty would be reduced from ±5.09% to ±3.22%, thereby reducing the uncertainty in royalty to ±$81 million. Going to composite sampling or on-line gas chromatographs could reduce sampling and analysis uncertainty further.

Establishing Minimum Sampling Frequency

In the development of Onshore Order 5, it will be necessary to establish sampling frequencies and methods that minimize the risk of mis-measurement, or uncertainty, of heating value and relative density. Onshore Order 5, III.C.23 currently requires annual sampling for all sales and allocation meters. From Appendices 3 and 4, it can be seen that annual sampling leads to high levels of uncertainty in many situations.

There are a number of options to consider as described below:

1. *Establish prescriptive sampling frequencies based on volume*. For example, meters measuring more than 100 Mcf/day could be sampled quarterly, whereas meters measuring 100 Mcf/day or less could be sampled annually. While this option would be easy to implement, it does not necessarily achieve the desired results of minimizing uncertainty. For example, from Appendix 3, a quarterly sampling could produce very low uncertainty for well "Palm Tree Fed 34-4", in the Big George Coal (±0.26%), but would result in a relative high uncertainty for well "20-mile 23A-1313", in the Anderson Coal (±14.83%).

2. *Establish sampling frequencies based on volume and formation*. For example, meters measuring gas from the Anderson Coal, over a certain volume threshold, would have to sample monthly, whereas meters measuring gas from the Big George Coal would only be required to sample annually. This method would be effective and relative easy to enforce. Unfortunately, it would also take a great deal more research as the values in Table 5 may not represent the true variability of each formation.

3. *Establish an uncertainty limit for heating value, similar to the uncertainty limit already established for volume measurement*. While this approach would ensure that BLM regulates sampling uncertainty, it could be difficult to enforce. For each point of measurement, the historical heating values would be needed to implement the methodologies presented in this study. Volume measurement uncertainty, by contrast, can be determined with a single field visit. Implementing this option would require that all samples from all Federal and Indian points of measurement be submitted to BLM and entered into a database. With this in place, a BLM inspector could easily find the heating value and relative density uncertainty for a specific meter.

4. *Establish an uncertainty limit for energy rather than having individual uncertainties for volume and heating value.* This approach would be the most effective method because royalties are ultimately based on energy and not just volume or heating value. It would also offer the most flexibility for industry as they could make up for a high sampling uncertainty with lower volume uncertainties. However, this would require a data base explained in the number 3, above.

5. *Establish an initial sampling frequency that could later be modified once there were enough data to perform an analysis.* The initial frequency could be relatively restrictive – once a month, for example, and put the burden on industry to provide the data to demonstrate a less frequent sampling is warranted, based on the methodology presented in this study. This would be on a case-by-case or area-by-area basis. Downsides to this approach would be the creation of a large workload for BLM in reviewing the data submitted and approving and tracking lesser sampling frequencies.

The BLM Onshore Order 5 team will be considering all options in the development of a draft Onshore Order 5.

Factors potentially affecting gas variability

In addition to the simulation-based analysis described above, numerous analyses were conducted on the data provided in an attempt to identify factors that lead to a higher degree of variability. These analyses included:

- heating value;
- temperature;
- time of production;
- pressure;
- reservoir type
- type of lift; and,
- the existence of a separator prior to the meter.

Heating value

For each meter, the average heating value was determined and then the meters were separated into one of 3 categories depending on the average heating value. The categories were defined in order to have about the same number of meters in each, as follows:

Low:	less than 1080 Btu/scf
Medium:	1081 to 1141 Btu/scf
High:	more than 1141 Btu/scf

For each meter, the 95%-confidence variation using the student-t distribution was plotted against the average time between samples. Meters with fewer than 5 samples were excluded from the analysis. Figure 9 shows the results of this analysis. Although it appears that the *medium* category shows slightly less variability overall, there is no apparent trend in variability versus sampling frequency for any of the three categories.

Temperature

For this analysis, the sample temperature was plotted against heating value for each meter. In order to plot all the data on a single graph, both the heating values and sample temperatures were normalized to 1200 Btu/scf and 60^{0}F, respectively. Because richer gases (higher heating value) are more prone to temperature effects, only the “High” heating value category was used. Meters with less than 5 samples were excluded from this analysis. In addition, only 39% of the samples taken included sample temperature, thereby limiting the amount of data to work with.

Figure 10 shows the plot of normalized heating value as a function of normalized temperature. There is no apparent dependency of temperature on heating value.

Time of production

The heating values from meters in each formation were plotted against the sample date in order to indentify common trends in the data – for example, if there were rapid changes in heating value early in the life of a well. Figures 11a – 11d show sample plots from the same formations used in Figures 4a – 4d. While some meters exhibit a trend over time, there is no commonality in the data. In other words, taking more frequent samples early in the life of a well does not seem to be justified by these graphs.

Pressure

For each meter, the average static pressure was used to categorize the meter as follows:

Low:	less than 50 psig
Medium:	between 51 and 500 psig
High:	greater than 500 psig

For each meter, the 95%-confidence variation using the student-t distribution was plotted against the average time between samples. Meters with fewer than 5 samples were excluded from the analysis. Figure 12 shows the results of this analysis. There is no apparent trend or dependency of heating value variability on static pressure.

Reservoir type

The meters were categorized according to the type of reservoir as follows: coal bed methane, gas cap, retrograde, and tight sands. For each meter, the 95%-confidence variation using the student-t distribution was plotted against the average time between samples. Meters with fewer than 5 samples were excluded from the analysis. Figure 13 shows the results of this analysis. There is no apparent trend or dependency of heating value variability on reservoir type.

Type of lift

The meters were categorized as to the type of lift: free flowing, plunger lift, and pumping unit. For each meter, the 95%-confidence variation using the student-t distribution was plotted against the average time between samples. Meters with fewer than 5 samples were excluded from the analysis. Figure 14 shows the results of this analysis. There is no apparent trend or dependency of heating value variability on lift type.

Existence of a separator prior to the meter

The meters were categorized as to whether or not there was a separator prior to the meter. For each meter, the 95%-confidence variation using the student-t distribution was plotted against the average time between samples. Meters with fewer than 5 samples were excluded from the analysis. Figure 15 shows the results of this analysis. There is no apparent trend or dependency of heating value variability on the existence of a separator.

Flow rate

The meters were categorized by flow rate as follows:

Low: Less than 50 Mcf/day
Medium: Between 50 and 100 Mcf/day
High: Between 100 and 500 Mcf/day
Very High: Greater than 500 Mcf/day

For each meter, the 95%-confidence variation using the student-t distribution was plotted against the average time between samples. Meters with fewer than 5 samples were excluded from the analysis. Figure 17 shows the results of this analysis. While the "Very High" category appears to have less variation, there were only 7 meters in this category, which is not enough to make a statistically significant conclusion.

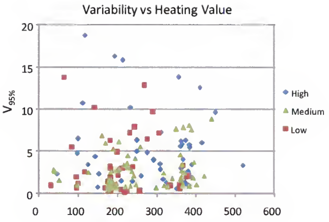
Variability vs Heating Value

Figure 9

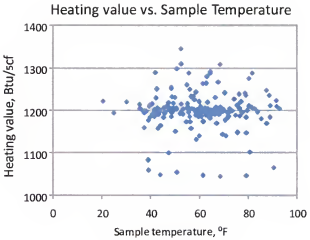
Heating value vs. Sample Temperature

Figure 10

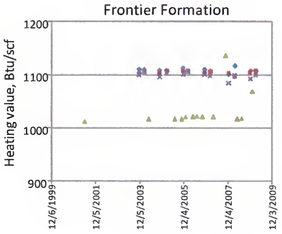
Frontier Formation

Figure 11a

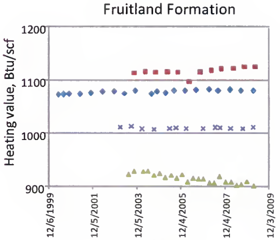
Fruitland Formation

Figure 11b

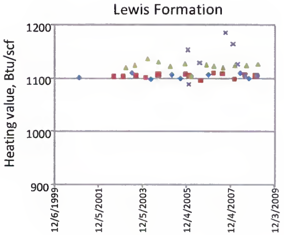
Lewis Formation

Figure 11c

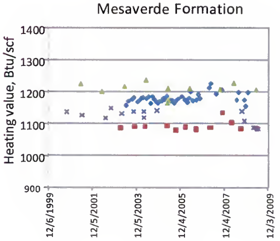
Mesaverde Formation

Figure 11d

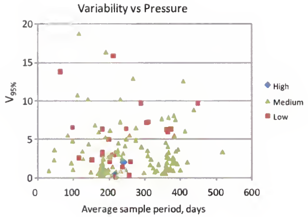

Figure 12

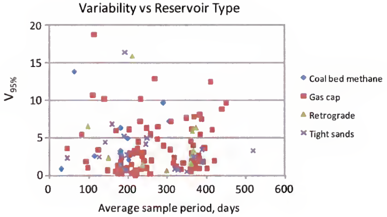

Figure 13

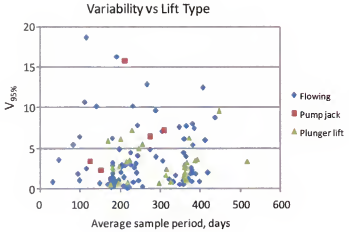

Figure 15

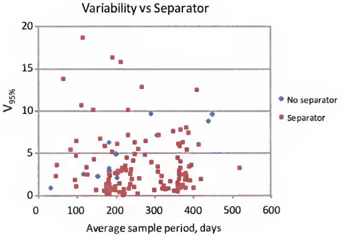

Figure 16

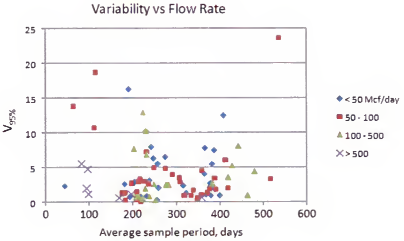

Figure 17

Appendix 1 – Sample Calculation of Heating Value Variability and Uncertainty

To demonstrate the methodology for determining heating value variability ($V_{95\%}$), a meter "S 25-34" measuring gas from the Almy Formation will be used. Gas analysis data for this meter was obtained for the past 6 years as shown in columns (1) and (2) from Table 1-1 below. The average heating value is 1162.233 Btu/scf for the gas analyses shown. The standard deviation of the data is calculated with the following equation:

(Eq. 1-1)

Where

σ is the standard deviation, Btu/scf
HV_i indicates an individual heating value
n is the number of heating values (12 in this example)
is the average heating value, Btu/scf

(1) Sample Date	(2) Heating Value (Btu/scf)	(3)
6/26/03	1153.135	101.9748
1/15/04	1165.056	3.323116
6/25/04	1142.626	424.6838
12/11/04	1154.601	74.52797
6/14/05	1150.726	156.439
1/26/06	1166.713	12.10373
5/8/06	1159.017	17.77768
12/4/06	1179.779	273.7583
6/11/07	1159.117	16.94358
12/7/07	1186.447	538.8499
8/29/08	1179.102	251.817
1/15/09	1162.483	0.562888
Average:	1163.233	
Sum:		1872.762

Table 1-1

For this example the sum of 1872.762 is the sum of the square of the difference between the individual heating values and the average heating value (Table 1-1, column (3)), so the standard deviation is:

= ±13.05 Btu/scf

For 12 samples, the variable t_{dist} is 2.201 (see Appendix 2), therefore the uncertainty at a 95% confidence level is:

$$V_{95\%} = 13.05 \times 2.201 = \pm 28.73 \text{ Btu/scf}$$

Finally, converting this into a percentage gives a variability of:

$$= \pm 2.47\%$$

From the variability, the uncertainty in average heating value (UHV) can then be calculated as follows:

Table 1-2 shows the uncertainty in 1-year average heating value for 30, 60, 180, and 365 day sampling periods.

Sampling Period (days)	U_{HV} (±%)
30	0.668
60	0.944
90	1.157
180	1.636
365	2.330

Table 1-2

Appendix 2 – Student t distribution function

#Samples	t-dist	#Samples	t-dist	#Samples	t-dist
		40	2.023	160	1.975
		41	2.021	165	1.975
2	12.706	42	2.020	170	1.974
3	4.303	43	2.018	175	1.974
4	3.182	44	2.017	180	1.973
5	2.776	45	2.015	185	1.973
6	2.571	46	2.014	190	1.973
7	2.447	47	2.013	195	1.972
8	2.365	48	2.012	200	1.972
9	2.306	49	2.011	205	1.972
10	2.262	50	2.010	250	1.970
11	2.228	51	2.009	300	1.968
12	2.201	52	2.008	350	1.967
13	2.179	53	2.007	400	1.966
14	2.160	54	2.006	450	1.965
15	2.145	55	2.005	500	1.965
16	2.131	56	2.004	600	1.964
17	2.120	57	2.003	700	1.963
18	2.110	58	2.002	800	1.963
19	2.101	59	2.002	∞	1.960
20	2.093	60	2.001		
21	2.086	65	1.998		
22	2.080	70	1.995		
23	2.074	75	1.993		
24	2.069	80	1.990		
25	2.064	85	1.989		
26	2.060	90	1.987		
27	2.056	95	1.986		
28	2.052	100	1.984		
29	2.048	105	1.983		
30	2.045	110	1.982		
31	2.042	115	1.981		
32	2.040	120	1.980		
33	2.037	125	1.979		
34	2.035	130	1.979		
35	2.032	135	1.978		
36	2.030	140	1.977		
37	2.028	145	1.977		
38	2.026	150	1.976		
39	2.024	155	1.975		

Appendix 3 – 1-Year Average Heating Value Uncertainty by Formation

Formation	Meter Name	#samples	$V_{95\%}$	Sample Period			
				1-month	3-month	6-month	1-year
ALMOND	Meter 1	13	2.62	0.71	1.24	1.75	2.49
	Meter 2	7	2.54	0.69	1.20	1.70	2.42
	Meter 3	4	2.91	0.79	1.37	1.94	2.76
	Meter 4	5	5.27	1.44	2.49	3.52	5.02
ALMY	Meter 5	4	8.20	2.24	3.87	5.48	7.80
	Meter 6	6	5.92	1.62	2.80	3.96	5.63
	Meter 7	7	6.24	1.70	2.95	4.17	5.94
	Meter 8	12	2.47	0.67	1.17	1.65	2.35
ANDERSON COAL	Meter 9	8	31.41	8.56	14.83	20.98	29.87
	Meter 10	12	2.58	0.70	1.22	1.73	2.46
BAXTER	Meter 11	5	3.33	0.91	1.57	2.22	3.16
	Meter 12	6	6.34	1.73	2.99	4.23	6.03
	Meter 13	4	6.77	1.85	3.20	4.52	6.44
BEAR RIVER/FRONTIER 2	Meter 14	52	2.64	0.72	1.25	1.77	2.52
BIG GEORGE COAL	Meter 15	7	1.45	0.39	0.68	0.97	1.38
	Meter 16	4	0.56	0.15	0.26	0.37	0.53
	Meter 17	4	3.21	0.88	1.52	2.15	3.06
CANYON COAL	Meter 18	8	7.19	1.96	3.39	4.80	6.83
	Meter 19	7	26.67	7.27	12.59	17.81	25.36
CARMEL	Meter 20	11	1.13	0.31	0.53	0.76	1.08
CASTLEGATE	Meter 21	10	3.60	0.98	1.70	2.41	3.43
	Meter 22	14	3.02	0.82	1.43	2.02	2.87
CHACRA	Meter 23	7	1.90	0.52	0.90	1.27	1.81
	Meter 24	6	12.56	3.43	5.93	8.39	11.95
	Meter 25	6	1.99	0.54	0.94	1.33	1.89
	Meter 26	6	1.28	0.35	0.61	0.86	1.22
	Meter 27	6	2.62	0.71	1.24	1.75	2.49
COOK COAL	Meter 28	4	2.91	0.79	1.38	1.95	2.77
COW CREEK	Meter 29	5	5.57	1.52	2.63	3.72	5.30
DAKOTA	Meter 30	5	16.35	4.46	7.72	10.92	15.55
	Meter 31	4	3.56	0.97	1.68	2.37	3.38
	Meter 32	7	3.53	0.96	1.67	2.36	3.36
	Meter 33	6	7.69	2.10	3.63	5.14	7.31
	Meter 34	6	8.10	2.21	3.83	5.41	7.70
	Meter 35	6	2.38	0.65	1.12	1.59	2.26
	Meter 36	6	4.10	1.12	1.94	2.74	3.90
	Meter 37	6	6.10	1.66	2.88	4.07	5.80
DAKOTA / MORRISON	Meter 38	7	0.94	0.26	0.44	0.63	0.89
DIETZ 3 COAL	Meter 39	4	1.12	0.31	0.53	0.75	1.07
ERICSON	Meter 40	4	1.81	0.49	0.85	1.21	1.72
FARMINGTON	Meter 41	4	0.18	0.05	0.09	0.12	0.17
	Meter 42	6	7.54	2.06	3.56	5.04	7.17
FELIX COAL	Meter 43	4	4.23	1.15	2.00	2.82	4.02
FORT UNION	Meter 44	12	3.28	0.89	1.55	2.19	3.12
	Meter 45	7	0.60	0.16	0.28	0.40	0.57
FORT UNION COAL	Meter 46	13	2.97	0.81	1.40	1.99	2.83
	Meter 47	12	4.98	1.36	2.35	3.32	4.73
FRONTIER	Meter 48	6	1.63	0.45	0.77	1.09	1.55
	Meter 49	12	0.76	0.21	0.36	0.51	0.72
	Meter 50	12	0.55	0.15	0.26	0.37	0.52
	Meter 51	12	1.17	0.32	0.55	0.78	1.11
	Meter 52	6	3.02	0.82	1.43	2.02	2.87
	Meter 53	5	6.18	1.69	2.92	4.13	5.88
	Meter 54	5	1.00	0.27	0.47	0.67	0.95
	Meter 55	13	7.25	1.98	3.42	4.84	6.89
FRONTIER 2	Meter 56	6	3.71	1.01	1.75	2.47	3.52

Formation	Meter Name	#samples	$V_{95\%}$	Sample Period 1-month	3-month	6-month	1-year
FRUITLAND	Meter 57	20	0.61	0.17	0.29	0.41	0.58
	Meter 58	7	4.58	1.25	2.16	3.06	4.35
	Meter 59	12	1.43	0.39	0.68	0.96	1.36
	Meter 60	7	1.76	0.48	0.83	1.18	1.68
	Meter 61	12	0.99	0.27	0.47	0.66	0.94
	Meter 62	5	10.23	2.79	4.83	6.83	9.73
	Meter 63	5	2.71	0.74	1.28	1.81	2.57
	Meter 64	23	1.95	0.53	0.92	1.30	1.86
	Meter 65	13	0.33	0.09	0.15	0.22	0.31
FRUITLAND COAL	Meter 66	22	1.14	0.31	0.54	0.76	1.08
GALLUP	Meter 67	7	7.50	2.04	3.54	5.01	7.13
	Meter 68	10	0.29	0.08	0.13	0.19	0.27
	Meter 69	6	2.25	0.61	1.06	1.50	2.14
	Meter 70	4	0.55	0.15	0.26	0.36	0.52
GREEN RIVER	Meter 71	9	0.34	0.09	0.16	0.22	0.32
	Meter 72	5	13.84	3.77	6.54	9.24	13.16
	Meter 73	5	5.61	1.53	2.65	3.75	5.34
HILLIARD/BAXTER	Meter 74	47	3.65	1.00	1.72	2.44	3.47
KNOBLOCH COAL	Meter 75	18	0.94	0.26	0.44	0.63	0.89
LANCE	Meter 76	7	0.61	0.17	0.29	0.40	0.58
LANCE POOL	Meter 77	8	1.08	0.30	0.51	0.72	1.03
	Meter 78	7	0.46	0.13	0.22	0.31	0.44
	Meter 79	6	2.07	0.56	0.98	1.38	1.97
	Meter 80	4	0.92	0.25	0.43	0.61	0.88
	Meter 81	4	1.18	0.32	0.56	0.79	1.12
LANCE POOL TRANSILANCE POOL	Meter 82	13	0.43	0.12	0.20	0.29	0.41
LANCE/WARDELL	Meter 83	11	0.77	0.21	0.36	0.51	0.73
LEWIS	Meter 84	6	3.48	0.95	1.64	2.32	3.31
	Meter 85	7	5.01	1.37	2.37	3.35	4.77
	Meter 86	10	0.81	0.22	0.38	0.54	0.77
	Meter 87	6	3.36	0.92	1.59	2.25	3.20
	Meter 88	8	2.91	0.79	1.37	1.94	2.77
	Meter 89	4	1.82	0.50	0.86	1.21	1.73
	Meter 90	8	6.86	1.87	3.24	4.58	6.52
	Meter 91	13	0.80	0.22	0.38	0.53	0.76
	Meter 92	13	1.49	0.41	0.70	0.99	1.42
	Meter 93	9	4.42	1.21	2.09	2.95	4.21
LOWER CANYON COAL	Meter 94	10	2.14	0.58	1.01	1.43	2.03
LOWER COOK COAL	Meter 95	4	5.56	1.51	2.62	3.71	5.28
MANCOS B	Meter 96	4	6.45	1.76	3.04	4.31	6.13
MESAVERDE	Meter 97	8	4.53	1.24	2.14	3.03	4.31
	Meter 98	7	0.94	0.26	0.45	0.63	0.90
	Meter 99	7	1.85	0.51	0.88	1.24	1.76
	Meter 100	45	2.37	0.65	1.12	1.58	2.25
	Meter 101	9	0.90	0.25	0.43	0.60	0.86
	Meter 102	6	0.99	0.27	0.47	0.66	0.95
	Meter 103	11	2.98	0.81	1.41	1.99	2.83
	Meter 104	11	3.07	0.84	1.45	2.05	2.92
	Meter 105	12	2.88	0.79	1.36	1.93	2.74
	Meter 106	10	2.65	0.72	1.25	1.77	2.52
	Meter 107	7	2.06	0.56	0.97	1.38	1.96
	Meter 108	11	2.74	0.75	1.30	1.83	2.61
	Meter 109	6	1.13	0.31	0.53	0.75	1.07
	Meter 110	11	4.02	1.10	1.90	2.68	3.82
	Meter 111	10	1.50	0.41	0.71	1.00	1.43
	Meter 112	5	4.80	1.31	2.27	3.21	4.57
	Meter 113	14	4.19	1.14	1.98	2.80	3.99
	Meter 114	8	2.51	0.69	1.19	1.68	2.39
MESAVERDE 1	Meter 115	12	0.70	0.19	0.33	0.47	0.66
	Meter 116	6	8.84	2.41	4.17	5.90	8.40
	Meter 117	17	2.34	0.64	1.11	1.56	2.23
	Meter 118	8	15.85	4.32	7.49	10.59	15.08
MESAVERDE 1/LANCE	Meter 119	6	0.57	0.16	0.27	0.38	0.54
MORGAN	Meter 120	4	1.15	0.31	0.55	0.77	1.10
MORRISON	Meter 121	12	0.73	0.20	0.34	0.49	0.69

Formation	Meter Name	#samples	$V_{95\%}$	Sample Period 1-month	3-month	6-month	1-year
MUDDY	Meter 122	13	5.98	1.63	2.83	4.00	5.69
NACIMIENTO	Meter 123	38	5.53	1.51	2.61	3.69	5.26
	Meter 124	13	1.39	0.38	0.66	0.93	1.32
OJO ALAMO	Meter 125	12	1.96	0.53	0.93	1.31	1.86
	Meter 126	8	3.18	0.87	1.50	2.13	3.03
	Meter 127	12	0.28	0.08	0.13	0.19	0.27
	Meter 128	6	5.51	1.50	2.60	3.68	5.24
	Meter 129	10	10.25	2.79	4.84	6.84	9.74
PICTURED CLIFFS	Meter 130	19	10.75	2.93	5.07	7.18	10.22
	Meter 131	8	0.44	0.12	0.21	0.29	0.42
	Meter 132	9	4.91	1.34	2.32	3.28	4.67
	Meter 133	7	1.92	0.52	0.91	1.28	1.83
PINON FRUITLAND SAND	Meter 134	5	1.35	0.37	0.64	0.90	1.28
	Meter 135	6	2.13	0.58	1.00	1.42	2.02
	Meter 136	11	12.92	3.52	6.10	8.63	12.29
POINT LOOKOUT	Meter 137	5	23.64	6.44	11.16	15.78	22.48
	Meter 138	7	0.59	0.16	0.28	0.39	0.56
	Meter 139	8	7.94	2.17	3.75	5.31	7.56
ROBERTSON COAL	Meter 140	27	13.83	3.77	6.53	9.24	13.15
S1-FRONTIER 1/S2-BEAR RIVER	Meter 141	7	1.71	0.47	0.81	1.14	1.63
S1-FRONTIER 1/S2-FRONTIER 2	Meter 142	6	2.68	0.73	1.26	1.79	2.55
	Meter 143	7	0.69	0.19	0.33	0.46	0.66
S1-FRONTIER/S3-BAXTER	Meter 144	5	2.01	0.55	0.95	1.34	1.91
	Meter 145	7	1.08	0.29	0.51	0.72	1.02
SAN JOSE	Meter 146	13	1.28	0.35	0.61	0.86	1.22
	Meter 147	6	7.85	2.14	3.71	5.24	7.46
SHANNON	Meter 148	5	2.11	0.57	1.00	1.41	2.00
TANSILL	Meter 149	5	1.35	0.37	0.64	0.90	1.28
TOCITO	Meter 150	19	18.73	5.11	8.84	12.51	17.81
TRANSITION	Meter 151	18	3.46	0.94	1.63	2.31	3.29
	Meter 152	8	7.26	1.98	3.43	4.85	6.91
TRANSITION/MESAVERDE 1	Meter 153	5	9.68	2.64	4.57	6.46	9.20
TURNER	Meter 154	11	1.44	0.39	0.68	0.96	1.37
UINTA	Meter 155	11	0.12	0.03	0.06	0.08	0.12
UPPER COOK COAL	Meter 156	6	9.72	2.65	4.59	6.49	9.24
WASATCH	Meter 157	21	6.55	1.78	3.09	4.37	6.22
	Meter 158	6	6.52	1.78	3.08	4.35	6.20
	Meter 159	4	2.15	0.59	1.02	1.44	2.05
	Meter 160	5	2.42	0.66	1.14	1.62	2.30
	Meter 161	6	1.01	0.28	0.48	0.68	0.96
	Meter 162	11	3.38	0.92	1.60	2.26	3.21
	Meter 163	11	6.37	1.74	3.01	4.26	6.06
	Meter 164	10	0.84	0.23	0.40	0.56	0.80
	Meter 165	12	1.40	0.38	0.66	0.93	1.33
	Meter 166	12	1.18	0.32	0.56	0.79	1.13
	Meter 167	12	1.74	0.47	0.82	1.16	1.65
	Meter 168	12	0.81	0.22	0.38	0.54	0.77
	Meter 169	12	0.94	0.26	0.45	0.63	0.90
	Meter 170	9	1.61	0.44	0.76	1.08	1.53
WILLIAMS FORK	Meter 171	10	2.77	0.76	1.31	1.85	2.63
WOLF CAMP	Meter 172	4	1.60	0.44	0.76	1.07	1.52
WYODAK COAL	Meter 173	12	6.34	1.73	2.99	4.23	6.03
?	Meter 174	56	2.81	0.77	1.33	1.88	2.68
?	Meter 175	42	1.55	0.42	0.73	1.04	1.48
?	Meter 176	9	0.67	0.18	0.32	0.45	0.64
?	Meter 177	6	3.44	0.94	1.62	2.30	3.27
?	Meter 178	6	5.84	1.59	2.76	3.90	5.55
?	Meter 179	6	0.84	0.23	0.40	0.56	0.80
?	Meter 180	23	1.08	0.29	0.51	0.72	1.03

Appendix 4 - 1-Year Average Relative Density Uncertainty by Formation

Formation	Meter Name	#samples	$V_{95\%}$	Sample Period			
				1-month	3-month	6-month	1-year
ALMOND	Meter 1	13	3.22	0.88	1.52	2.15	3.06
	Meter 2	7	2.27	0.62	1.07	1.51	2.16
	Meter 3	4	3.40	0.93	1.60	2.27	3.23
	Meter 4	5	3.48	0.95	1.64	2.32	3.31
ALMY	Meter 5	4	9.99	2.72	4.72	6.67	9.50
	Meter 6	6	10.39	2.83	4.91	6.94	9.88
	Meter 7	7	8.27	2.26	3.91	5.53	7.87
	Meter 8	12	4.41	1.20	2.08	2.94	4.19
ANDERSON COAL	Meter 9	8	19.98	5.45	9.44	13.35	19.01
	Meter 10	12	3.53	0.96	1.67	2.36	3.36
BAXTER	Meter 11	5	1.97	0.54	0.93	1.32	1.87
	Meter 12	6	8.18	2.23	3.86	5.46	7.78
	Meter 13	4	8.28	2.26	3.91	5.53	7.88
BEAR RIVER/FRONTIER 2	Meter 14	52	2.70	0.74	1.27	1.80	2.57
BIG GEORGE COAL	Meter 15	7	2.28	0.62	1.08	1.53	2.17
	Meter 16	4	2.85	0.78	1.35	1.90	2.71
	Meter 17	4	1.55	0.42	0.73	1.03	1.47
CANYON COAL	Meter 18	8	5.09	1.39	2.40	3.40	4.84
	Meter 19	7	18.14	4.95	8.57	12.12	17.26
CARMEL	Meter 20	11	1.32	0.36	0.62	0.88	1.25
CASTLEGATE	Meter 21	10	4.97	1.36	2.35	3.32	4.73
	Meter 22	14	3.74	1.02	1.76	2.49	3.55
CHACRA	Meter 23	7	2.00	0.55	0.95	1.34	1.91
	Meter 24	6	10.36	2.82	4.89	6.92	9.85
	Meter 25	6	2.31	0.63	1.09	1.54	2.19
	Meter 26	6	1.51	0.41	0.71	1.01	1.44
	Meter 27	6	2.77	0.76	1.31	1.85	2.63
COOK COAL	Meter 28	4	3.69	1.01	1.74	2.46	3.51
COW CREEK	Meter 29	5	7.24	1.98	3.42	4.84	6.89
DAKOTA	Meter 30	5	9.43	2.57	4.45	6.30	8.97
	Meter 31	4	4.24	1.16	2.00	2.83	4.03
	Meter 32	7	3.79	1.03	1.79	2.53	3.61
	Meter 33	6	8.16	2.22	3.85	5.45	7.76
	Meter 34	6	9.17	2.50	4.33	6.12	8.72
	Meter 35	6	2.65	0.72	1.25	1.77	2.52
	Meter 36	6	5.19	1.42	2.45	3.47	4.94
	Meter 37	6	6.55	1.79	3.09	4.37	6.23
DAKOTA / MORRISON	Meter 38	7	0.99	0.27	0.47	0.66	0.94
DIETZ 3 COAL	Meter 39	4	12.71	3.47	6.00	8.49	12.09
ERICSON	Meter 40	4	2.09	0.57	0.99	1.40	1.99
FARMINGTON	Meter 41	4	0.16	0.04	0.08	0.11	0.15
	Meter 42	6	5.07	1.38	2.40	3.39	4.82
FELIX COAL	Meter 43	4	0.90	0.25	0.43	0.60	0.86
FORT UNION	Meter 44	12	4.41	1.20	2.08	2.94	4.19
	Meter 45	7	0.26	0.07	0.12	0.17	0.25
FORT UNION COAL	Meter 46	13	4.39	1.20	2.07	2.93	4.17
	Meter 47	12	6.30	1.72	2.97	4.21	5.99
FRONTIER	Meter 48	6	1.74	0.47	0.82	1.16	1.65
	Meter 49	12	0.85	0.23	0.40	0.57	0.81
	Meter 50	12	0.64	0.17	0.30	0.42	0.60
	Meter 51	12	1.39	0.38	0.66	0.93	1.33
	Meter 52	6	4.42	1.20	2.09	2.95	4.20
	Meter 53	5	7.04	1.92	3.32	4.70	6.69
	Meter 54	5	1.90	0.52	0.90	1.27	1.81
	Meter 55	13	10.93	2.98	5.16	7.30	10.40
FRONTIER 2	Meter 56	6	4.30	1.17	2.03	2.87	4.09

				Sample Period			
Formation	Meter Name	#samples	$V_{95\%}$	1-month	3-month	6-month	1-year
FRUITLAND	Meter 57	20	0.92	0.25	0.44	0.62	0.88
	Meter 58	7	4.92	1.34	2.32	3.29	4.68
	Meter 59	12	1.88	0.51	0.89	1.26	1.79
	Meter 60	7	2.31	0.63	1.09	1.54	2.20
	Meter 61	12	0.90	0.25	0.42	0.60	0.86
	Meter 62	5	7.89	2.15	3.73	5.27	7.51
	Meter 63	5	3.26	0.89	1.54	2.18	3.10
	Meter 64	23	3.10	0.85	1.47	2.07	2.95
	Meter 65	13	0.86	0.23	0.40	0.57	0.81
FRUITLAND COAL	Meter 66	22	0.99	0.27	0.47	0.66	0.94
GALLUP	Meter 67	7	6.41	1.75	3.03	4.28	6.10
	Meter 68	10	1.08	0.29	0.51	0.72	1.03
	Meter 69	6	2.29	0.62	1.08	1.53	2.18
	Meter 70	4	1.57	0.43	0.74	1.05	1.50
GREEN RIVER	Meter 71	5	16.03	4.37	7.57	10.70	15.24
	Meter 72	5	6.27	1.71	2.96	4.18	5.96
	Meter 73	9	0.50	0.14	0.24	0.34	0.48
HILLIARD/BAXTER	Meter 74	47	3.88	1.06	1.83	2.59	3.69
KNOBLOCH COAL	Meter 75	18	0.57	0.16	0.27	0.38	0.55
LANCE	Meter 76	7	1.23	0.33	0.58	0.82	1.17
LANCE POOL	Meter 77	8	1.74	0.47	0.82	1.16	1.65
	Meter 78	7	0.49	0.13	0.23	0.33	0.47
	Meter 79	6	2.25	0.61	1.06	1.50	2.14
	Meter 80	4	1.04	0.28	0.49	0.69	0.98
	Meter 81	4	1.92	0.52	0.91	1.28	1.82
LANCE POOL TRANSILANCE POOL	Meter 82	13	0.54	0.15	0.26	0.36	0.52
LANCE/WARDELL	Meter 83	11	1.01	0.28	0.48	0.68	0.96
LEWIS	Meter 84	6	3.46	0.94	1.63	2.31	3.29
	Meter 85	7	5.31	1.45	2.51	3.55	5.05
	Meter 86	10	0.96	0.26	0.45	0.64	0.91
	Meter 87	6	4.05	1.11	1.91	2.71	3.86
	Meter 88	8	2.83	0.77	1.34	1.89	2.69
	Meter 89	4	1.90	0.52	0.90	1.27	1.81
	Meter 90	8	10.78	2.94	5.09	7.20	10.25
	Meter 91	13	3.28	0.89	1.55	2.19	3.12
	Meter 92	13	1.93	0.53	0.91	1.29	1.84
	Meter 93	9	6.50	1.77	3.07	4.34	6.18
LOWER CANYON COAL	Meter 94	10	1.55	0.42	0.73	1.03	1.47
LOWER COOK COAL	Meter 95	4	3.02	0.82	1.43	2.02	2.88
MANCOS B	Meter 96	4	2.88	0.79	1.36	1.93	2.74
MESAVERDE	Meter 97	8	6.18	1.69	2.92	4.13	5.88
	Meter 98	7	3.48	0.95	1.64	2.32	3.31
	Meter 99	7	1.74	0.47	0.82	1.16	1.65
	Meter 100	45	3.84	1.05	1.82	2.57	3.66
	Meter 101	9	1.06	0.29	0.50	0.71	1.01
	Meter 102	6	1.21	0.33	0.57	0.81	1.15
	Meter 103	11	4.93	1.34	2.33	3.29	4.69
	Meter 104	11	3.56	0.97	1.68	2.38	3.39
	Meter 105	12	3.57	0.97	1.69	2.39	3.40
	Meter 106	10	2.20	0.60	1.04	1.47	2.09
	Meter 107	7	1.84	0.50	0.87	1.23	1.75
	Meter 108	11	3.15	0.86	1.49	2.10	2.99
	Meter 109	6	1.34	0.37	0.63	0.90	1.28
	Meter 110	11	4.22	1.15	1.99	2.82	4.01
	Meter 111	10	1.56	0.42	0.73	1.04	1.48
	Meter 112	5	8.69	2.37	4.10	5.80	8.26
	Meter 113	14	3.30	0.90	1.56	2.20	3.14
	Meter 114	8	2.45	0.67	1.16	1.63	2.33
MESAVERDE 1	Meter 115	12	1.12	0.31	0.53	0.75	1.06
	Meter 116	6	5.39	1.47	2.54	3.60	5.12
	Meter 117	17	4.18	1.14	1.97	2.79	3.97
	Meter 118	8	17.30	4.72	8.17	11.55	16.45
MESAVERDE 1/LANCE	Meter 119	6	0.34	0.09	0.16	0.23	0.32
MORGAN	Meter 120	4	0.98	0.27	0.46	0.65	0.93
MORRISON	Meter 121	12	1.03	0.28	0.49	0.69	0.98

				Sample Period			
Formation	Meter Name	#samples	$V_{95\%}$	1-month	3-month	6-month	1-year
MUDDY	Meter 122	13	2.11	0.57	1.00	1.41	2.01
NACIMIENTO	Meter 123	38	6.68	1.82	3.15	4.46	6.35
OJO ALAMO	Meter 124	13	0.83	0.23	0.39	0.56	0.79
	Meter 125	12	2.05	0.56	0.97	1.37	1.95
	Meter 126	8	1.53	0.42	0.72	1.02	1.46
PICTURED CLIFFS	Meter 127	12	0.46	0.13	0.22	0.31	0.44
	Meter 128	6	4.87	1.33	2.30	3.25	4.63
	Meter 129	10	10.95	2.98	5.17	7.31	10.41
	Meter 130	19	12.25	3.34	5.79	8.18	11.65
	Meter 131	8	0.67	0.18	0.32	0.45	0.64
	Meter 132	9	4.56	1.24	2.15	3.04	4.33
	Meter 133	7	1.58	0.43	0.74	1.05	1.50
PINON FRUITLAND SAND	Meter 134	5	1.97	0.54	0.93	1.32	1.88
POINT LOOKOUT	Meter 135	6	1.97	0.54	0.93	1.32	1.88
	Meter 136	11	15.31	4.17	7.23	10.22	14.56
	Meter 137	5	26.84	7.32	12.67	17.92	25.52
	Meter 138	7	3.78	1.03	1.78	2.52	3.59
	Meter 139	8	9.19	2.51	4.34	6.14	8.74
ROBERTSON COAL	Meter 140	27	16.33	4.45	7.71	10.90	15.53
S1-FRONTIER 1/S2-BEAR RIVER	Meter 141	7	7.42	2.02	3.51	4.96	7.06
S1-FRONTIER 1/S2-FRONTIER 2	Meter 142	6	2.98	0.81	1.41	1.99	2.83
	Meter 143	7	0.63	0.17	0.30	0.42	0.60
S1-FRONTIER/S3-BAXTER	Meter 144	5	3.96	1.08	1.87	2.64	3.76
SAN JOSE	Meter 145	7	0.98	0.27	0.46	0.65	0.93
	Meter 146	13	1.28	0.35	0.60	0.85	1.21
	Meter 147	6	10.85	2.96	5.12	7.25	10.32
SHANNON	Meter 148	5	2.57	0.70	1.22	1.72	2.45
TANSILL	Meter 149	5	1.62	0.44	0.76	1.08	1.54
TOCITO	Meter 150	19	18.74	5.11	8.85	12.51	17.82
TRANSITION	Meter 151	18	3.57	0.97	1.69	2.39	3.40
	Meter 152	8	10.08	2.75	4.76	6.73	9.58
TRANSITION/MESAVERDE 1	Meter 153	5	13.43	3.66	6.34	8.97	12.77
TURNER	Meter 154	11	1.89	0.52	0.89	1.26	1.80
UINTA	Meter 155	11	0.16	0.04	0.08	0.11	0.16
UPPER COOK COAL	Meter 156	6	9.13	2.49	4.31	6.10	8.68
WASATCH	Meter 157	21	8.00	2.18	3.78	5.34	7.60
	Meter 158	12	1.43	0.39	0.68	0.96	1.36
	Meter 159	6	7.11	1.94	3.36	4.75	6.77
	Meter 160	12	1.83	0.50	0.86	1.22	1.74
	Meter 161	12	1.62	0.44	0.76	1.08	1.54
	Meter 162	4	1.48	0.40	0.70	0.99	1.41
	Meter 163	5	2.81	0.77	1.33	1.87	2.67
	Meter 164	6	0.73	0.20	0.35	0.49	0.70
	Meter 165	11	3.37	0.92	1.59	2.25	3.21
	Meter 166	11	7.12	1.94	3.36	4.75	6.77
	Meter 167	9	1.61	0.44	0.76	1.07	1.53
	Meter 168	10	0.92	0.25	0.44	0.62	0.88
	Meter 169	12	1.16	0.32	0.55	0.78	1.10
	Meter 170	12	0.88	0.24	0.42	0.59	0.84
WILLIAMS FORK	Meter 171	10	2.22	0.61	1.05	1.48	2.11
WOLF CAMP	Meter 172	4	2.21	0.60	1.04	1.48	2.10
WYODAK COAL	Meter 173	12	9.81	2.67	4.63	6.55	9.33
?	Meter 174	56	3.23	0.88	1.53	2.16	3.08
?	Meter 175	42	2.40	0.65	1.13	1.60	2.28
?	Meter 176	9	3.18	0.87	1.50	2.13	3.03
?	Meter 177	6	3.98	1.09	1.88	2.66	3.79
?	Meter 178	6	4.26	1.16	2.01	2.85	4.06
?	Meter 179	6	0.93	0.25	0.44	0.62	0.88
?	Meter 180	23	1.14	0.31	0.54	0.76	1.09